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MILLIMETER WAVE, HIGH-RESOLUTION,
HOLOGRAPHIC SURVEILLANCE SYSTEM

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Millimeter wave, high-resolution, holographic surveillance system

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ABSTRACT

Millimeter wave holographic imaging systems capable of imaging through clothing to detect contraband, metal, plastic, or ceramic weapons may provide a practical solution to personnel inspection needs in mass transportation centers. Traditional inspection systems, such as metal detectors and x-ray imaging systems, have limitations for the detection of concealed weapons. Metal detectors are limited because they cannot detect plastic weapons and x-ray imaging systems are limited in use due to radiological health considerations. A prototype millimeter wave holographic surveillance system has been developed and demonstrated at the Pacific Northwest Laboratory (PNL). The prototype millimeter wave holographic surveillance system developed at PNL consists of a sequentially switched 2 x 64 element array coupled to a 35 GHz bi-static transceiver. The sequentially switched array of antennas can be used to obtain the holographic data at high speed by electronically sequencing the antennas along one dimension and performing a mechanical scan along the other dimension. A one-dimensional mechanical scan can be performed in about one second. The prototype system scans an aperture of 0.75 by 2.05 m. This system has been demonstrated and images have been obtained on volunteers at Sea-Tac International airport in Seattle, Washington.

1.0 INTRODUCTION

The millimeter wave holographic surveillance system is an exciting concept for personnel surveillance. Although millimeter wave holography was proposed some time ago for use in contraband detection, optimized imaging techniques and high speed computer processing were not yet available^{1,2}.

Because millimeter waves readily penetrate clothing barriers and have relative small wavelengths, high resolution images of concealed weapons on personnel can be obtained. In addition, millimeter waves are non-ionizing and therefore do not present a health problem to humans in this low power imaging system.

Millimeter wave holography is a wavefront reconstruction technique that uses both phase and amplitude measurements of the radiation scattered from the target. In contrast to conventional imaging, where the outcome is a two-dimensional projection of the object, three-dimensional information can be recorded by holography because the phase of the radiation is a linear function of the distance traveled. Once the two-dimensional distribution of phase and amplitude of the scattered wave has been measured and recorded, it can be computationally back-propagated to any plane away from the aperture to form the image.

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In this paper, a general overview of millimeter wave holographic imaging theory will be discussed along with the design of a first-of-a-kind prototype near-real time, millimeter wave surveillance system. In addition, feasibility imaging results from imaging through clothing barriers and airport testing at Sea-Tac International Airport in Seattle, Washington will be demonstrated.

2.0 HOLOGRAPHIC IMAGING METHOD

The amplitude and phase of scattered wavefronts from concealed weapons can be measured directly at millimeter wave frequencies. Magnitude and phase data allows the wavefront reconstruction method to be applied. The wavefront reconstruction, or holographic process mathematically back propagates the wavefront from the phase and amplitude measurement plane to the target plane to form the reconstructed image. Holography utilizes measurements obtained over a two-dimensional area or aperture. In millimeter wave holography, the hologram is formed by scanning the two-dimensional aperture with an antenna. The hologram data is digitized and store in a computer. A digital image reconstruction algorithm is applied to the stored holographic data to form the image. The image is then displayed on video monitor. The holographic reconstruction algorithm uses the Fast Fourier Transform (FFT) to obtain efficient and timely reconstructed images.

The imaging system demonstrated in this paper uses a scanning configuration that is referred to as simultaneous source-receiver scanning. This imaging technique doubles the phase shift that would be observed in the stationary source case. This doubling of the phase effectively increases the resolution by two. Expected lateral resolution of this system is

$$\delta = \frac{r}{L} \left(\frac{\lambda}{2} \right) \quad (1)$$

where r is the distance to the target, and L is the width of the aperture, and λ is the wavelength.

The holographic system shown here also provides for a depth of focus that is very narrow. The expected depth of focus is

$$\Delta r = \pm \frac{4}{3} \lambda \left(\frac{r}{L} \right)^2 \quad (2)$$

where r is the distance to the target, and L is the width of the aperture, and λ is the wavelength.

3.0 HOLOGRAPHIC IMAGING SYSTEM

Figure 1 shows the prototype near real-time millimeter wave holographic imaging system(MWHIS) used in airport testing. The system consists of three devices: 35 GHz holographic array, high-speed vertical scanner, and computer system. This system gathers holographic data over a 0.75 by 2.05 m aperture in approximately one second by scanning the holographic array vertically in one second. The computer controls the holographic data collection and also the holographic processing and image display.

Figure 1 also shows that the imaging system can image only one side at a time (shown is back view). The subject is required to turn for as many side views as are desired. This prototype system takes a snapshot of the subject. Future versions of the imaging system will be capable of real time imaging. Although the millimeter waves can penetrate clothing, they cannot penetrate the human body. Therefore, multiple views of the subject is necessary to obtain full surveillance.

3.1 Holographic array

To achieve near real time, a holographic array was fabricated to increase the speed of data collection over the imaging aperture. A unique feature of the array is that the transmit power is individually sequenced from channel to channel during scanning operation. The same is true with the receive system. The array consists of two rows of linear antenna elements that are positioned on top of each other. The top row is the receive array and the bottom row is the transmit array. Both arrays have a total of 64 elements (128 total). The array antenna spacing is $4/3$ of a wavelength at 35 GHz (wavelength = 0.86 cm in air). The transmit and receive arrays are separated from each other by 1.5 wavelengths at 35 GHz. The antenna elements are polyrod end fire antennas. The array's design used a binary switching tree structure. The array is fabricated with

Figure 1. Prototype near real-time millimeter wave holographic imaging system

Ka band (26.5 - 40 GHz) waveguide switches. Two types of switches are used in the array. One is a 1 by 8 pin diode switch and the other is a low insertion loss, ferrite latching switch.

The array is coupled to a waveguide homodyne transceiver system. The transceiver source uses a high "Q" cavity, Indium Phosphide Gunn oscillator. Most of the power generated from this source is sent to the transmit array. A portion of the oscillator power is redirected to the receiver and is used as a reference for the phase and amplitude measurements. The receiver consists basically of five components: two power dividers, two phase detectors, and a phase shifter. The reference signal is sent to one of the power dividers. The power divider splits the power and sends a portion of the signal to one of the phase detectors and portion of the signal to other phase detector through the phase shifter. The phase shifter varies the phase in the reference leg by 90 degrees. The receive array is coupled to the receiver with the second power divider. The power divider splits the receive signals and sends one portion to the phase detector whose reference signal has been shifted 90 degrees and the other portion to the second phase detector. Two signals are obtained from the receiver, which is the holographic data used to synthetically form the image. This data is sent to the computer for image processing.

Holographic imaging with millimeter wave arrays can only be performed if the array is identical in phase and amplitude from channel to channel. The calibration procedure involves calibrating for phase, amplitude, and DC offset in each array channel.

The first calibration scan involves scanning the aperture without a target or object in front of the imaging aperture. This is said to be "scanning in air" and provides a means to force the individual channels to the same DC offset value. The second scan involves a correction for phase and amplitude. In this scan, a metal rod is positioned diagonally across the imaging aperture in very close proximity to the array antennas. The rod is used as a "short circuit" calibration standard for the array.

Since the rod is at the same distance away from the array for every element, the path length or phase and the amplitude for each element should be the same. Variance in the phase, amplitude and DC offset can be corrected computationally in the computer with the information provided from these two calibration scans.

3.2 Fast vertical scanner

A mechanical scanner capable of moving a 28 kg. horizontal millimeter wave array vertically 2.05 m in one second was fabricated for the holographic imaging system. The scanner was fabricated to operate under computer control and also provide information on the array's exact location during transient with great accuracy. Figure 2 show the scanner and the array. The scanner was designed and built with the public in mind; for instance, the outside panels and support structure are pleasant looking and conceals the internal mechanical apparatus from sight. Furthermore, the scanner is designed and fabricated to operate quietly without causing safety concerns to the public and not generate loud noises during scanning. A thin, Gore-tex RF window, used to cover the aperture allows millimeter wave penetration through the barrier. Acoustical foam was used to reduce noise.

Figure 2. Fast vertical scanner and holographic array

3.3 Holographic processor and display system

A SUN 4/370 general purpose computer, which operates under UNIX and is installed on a VME backplane was used in the development of the near real-time holographic imaging system. Coupled with the computer are a calculation processor based on the Intel i860 chip, dual 1-MHz simultaneous sampled A/D converter, and a multi-purpose interface board with associated timer modules. The computer controls both the 35 GHz holographic array and the fast vertical scanner.

Before holographic imaging can be performed, the 35 GHz array must be calibrated. The holographic array calibration procedure has been discussed above. The calibration data is stored on the computer's hard disk and is used to correct the raw data from a typical image scan. The corrected data is then sent to the calculation processor where the digital holographic reconstruction algorithm is applied. The reconstructed image is stored on the computer's hard disk. The reconstructed image is also sent to the video display for viewing.

4.0 Holographic Imaging Results

Imaging studies consisted of an initial feasibility study and later airport testing of the near real time imaging system. The feasibility study was performed to determine whether millimeter wave holography was capable of penetrating various clothing barriers without degradation to imaging quality. In addition, imaging resolution was also verified to determine whether plastic and metal fire arms were identifiable. Airport testing was performed to obtain a large data base of various personnel in an airport environment.

4.1 Feasibility imaging study

Initial work was performed to determine if small firearms could be imaged through clothing barriers. These studies were performed with 35 GHz and 90 GHz single channel monostatic holographic transceivers. The transceivers were scanned on a x-y rectilinear scanner to form an image aperture. Typical scan times ranged from 10 - 20 minutes. Various clothing barriers were positioned between the firearms and the imaging transceiver to determine imaging quality through obscurant materials.

Figure 3 shows the imaging results of the Glock -17 through a layered barrier of 100% light polyester and 100% wool. The imaging results show 35 GHz and 90 GHz images of the Glock 17 through the clothing barrier. The aperture size is 35 cm x 35 cm and the sampling size is 256 x 256 for both images. As can be observed from the figures, little or no image degradation is observed. Figure 3a shows the imaging setup geometry. Figure 3b shows the optical image of the Glock 17. Figure 3c shows the 35 GHz holographic image of the Glock 17 through the clothing barrier. Figure 3d shows the 90 GHz image of the Glock 17 through the clothing.

It is demonstrated from these results that clothing barriers do not present significant problems to imaging concealed objects.

In initial imaging studies with the x-y linear scanner and 35 GHz transceiver, it was observed that the human body was unable to remain motionless during the scan duration. The body motion affected the phase and amplitude measurements of the scattered wavefronts and resulted in a blurring of the reconstructed image. From these initial results it was determined that a holographic scanning system fast enough to stop body motion was necessary to obtain high quality images of the humans.

Holographic Imaging - 35 GHz and 90 GHz

(a)

(c)

(b)

(d)

Figure 3. (a) Experimental setup for Glock-17 imaged through 100% heavy wool and 100% light polyester (layered) barrier. (b) Optical image of Glock-17. (c) 35 GHz holographic image of Glock-17 imaged through wool and polyester barrier. (d) 90 GHz holographic image of Glock-17 imaged through wool and polyester barrier.

Figure 4. (a) Back view of 35 GHz holographic image of medium build, medium height male with test gun concealed on blazer jacket. (b) Front view. (c) Left side view.

Figure 5. (a) Back view of 35 GHz holographic image of medium build, large height male. (b) Front view of volunteer. (c) Left side view.

Figure 6. (a) Back view of 35 GHz holographic image of medium build, tall female. (b) Front view. (c) Right side view.

4.2 Airport testing

Airport testing of the prototype holographic imaging system was conducted from March 28 to April 2, 1993 at Sea-Tac International Airport in Seattle, Washington. One hundred fifty people (111 men and 39 women) were imaged with the system on strictly a voluntary basis.

Optical images of the volunteers were not produced during the airport testing. Holographic data was gathered at the airport and taken back to the laboratory for reconstruction and evaluation.

During testing, four images of volunteers were taken; front, left, back, and right sides. The test duration for each volunteer was about 40 seconds. The scanner speed for the test was 1 meter/sec. with an acceleration of 1 meter/sec². The clothing material worn by each volunteer was recorded for future reference, as were other characteristics such as height and build. The aperture of the image was 0.75 m by 2.05 m. The sampling in the aperture was 128 x 512 (65,536 total). The volunteers stood away from scanner on the order of 0.4 m.

Power density measurement of 0.25 mW/cm² was obtained at the center of the antenna array and approximately 3-mm away from the center emitter during continuous operation. All measurements were below the controlled and uncontrolled limit of 10 mW/cm² given in the American National Standard (ANSI) and Institute of Electrical and Electronics Engineers (IEEE) standard C95.1-1992 for human exposure to millimeter waves⁴.

In millimeter wave holography, the reconstructed image focal plane can be chosen by the operator. The depth of focus for this imaging system is on the order of three centimeters. Since the thickness of the body is greater than three centimeters at all imaging positions, portions of the human body are in focus and other portions are out of focus. In the following figures, the focal planes were chosen to highlight a certain body area (e.g. head, arms, stomach, etc.).

Figure 4 shows the reconstructed holographic image of a medium build, medium height male. This volunteer was wearing a blazer, slacks, leather belt, and dress shoes. The volunteer concealed a test gun used for metal detector testing under his blazer. Figure 4a shows the test gun and the back view of the suspect. Figure 4b shows the front view. The image reconstruction focal depth is on the front surface of the stomach. The volunteer's head is slightly turned to the right. As can be observed, the arms and calf area are out of focus at this focal plane, due to the sharp depth of focus of a continuous wave imaging system. Figure 4c shows the left side of the volunteer. The focal plane is on the head. The volunteer's glasses can be observed in the image. The right arm in this figure is out of focus.

Figure 5 shows the holographic reconstructed image of a medium build, tall male. The volunteer was wearing a shirt, jeans, leather belt, tennis shoes, and a cap. He was holding a book in his left hand. Figure 5a is the back view. This view shows the back bone and shoulder blade skin contours. The head is clearly visible and millimeter waves penetrate readily through the hair. Figure 5b shows the front view. A large belt buckle can be observed in this image along with the chest definition. Other noticeable features are what appear to be a button on the stomach area, the navel, coins or similar items in the left pants pocket, and a notebook or badge on the upper left chest area. The reconstructed focal plane is on the stomach area and the arms and calves are out of focus. Figure 5c shows the left side of the body. The volunteer is carrying a book in this image. Some image aliasing or ghosting can be observed.

Figure 6 shows three views of a medium build, tall female. She was wearing a shirt, slacks, leather belt, and dress shoes. Also, she wore earrings, a ring on the right hand, and a watch on the left arm. Figure 6a is the back view. Figure 6b shows the front view with her head turned sideways. Coins or keys can be observed in her left front pants pocket. Figure 6c shows the right side view.

5.0 Conclusions

A Near-real time, large aperture, millimeter wave holographic imaging system has been demonstrated. Holographic techniques have been used to obtain high quality images of personnel and concealed images under clothing barriers. Furthermore, millimeter wave holography is a viable technology for use in imaging various metal and plastic targets/weapons through clothing barriers with little or no degradation of imaging quality. In addition, innocuous items such as pocket pens, coins, belt buckles, and plastic badges can be distinguished from real threats such as the Glock 17.

A continuous wave 35 GHz holographic system was demonstrated that obtained lateral resolution on the order of one centimeter and a depth resolution on the order of three centimeters. Typically the body is thicker than 3 cm, especially from the side, so the reconstructed images have out-of-focus information that slightly obscures the image quality. It was also shown that body tissue is very reflective to millimeter wave signals at 35 GHz. Body geometry and contours are readily identifiable in the holographic reconstructed images.

This work also demonstrated that millimeter wave holographic arrays can be phase and amplitude corrected by the computer for holographic imaging.

In addition, millimeter wave holographic surveillance systems can be fabricated with low illuminating power for safe operation, similar to "electronic eyes" in automatic door openers.

Imaging aliasing or ghosting is more likely to occur from under sampling across the body in the horizontal direction than from the vertical direction. The arms, legs and torso can be viewed as cylinders that reflect the millimeter waves with greater angular displacement in the horizontal direction than in the vertical direction.

6.0 Acknowledgments

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